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Soil Cleanup Levels for Polycyclic Aromatic Hydrocarbons (PAHs) Interim Guidance

Technical Resources Section

This document is intended to provide interim guidance on suggested generic soil cleanup levels for polycyclic aromatic hydrocarbons (PAHs) based on protection of groundwater quality and protection of human health from direct contact with contaminated soil via direct ingestion and through inhalation of volatiles and particulate matter. It includes a discussion of the technical background, toxicological basis, and qualifications and considerations for the appropriate use of these suggested values, and considerations for sampling. **The use of these suggested generic values for decisions regarding a given site, either by Department staff or other parties, without full consideration of their context and qualifications on their use is not appropriate.** The availability of the suggested generic residual contaminant levels (RCLs) for PAHs provided in this guidance is not in any way intended to preclude or discourage site-specific analysis and decisionmaking under s. NR 720.19, Wis. Adm. Code. This guidance also includes discussion of some site-specific issues related to PAH contamination. The suggested generic residual contaminant levels included in this document do not address other pathways, such as potential surface water impacts, which may be of concern at some sites.

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Background

Polycyclic aromatic hydrocarbons (PAHs) - also referred to as polynuclear aromatic hydrocarbons (PNAs) or polyaromatic hydrocarbons - are commonly contaminants of concern at petroleum contamination sites involving diesel fuel, fuel oils, waste oil, and crude oils. They are also typically found as contaminants at wood preserving sites (as major components of creosote) and at coal gas sites. Additionally, the PAHs are relatively recalcitrant compounds and are likely still to remain in petroleum-contaminated soils even after treatment. Thus, they present an issue for soil cleanup levels at many sites, and for the ultimate disposition of many petroleum-contaminated soils treated *ex situ*.

A recognized difficulty with implementation of ch. NR 720, Wis. Adm. Code, is the lack of specific cleanup levels for the polycyclic aromatic hydrocarbons (PAHs). The generic GRO/DRO soil cleanup levels included in s. NR 720.09(4), Wis. Adm. Code, were developed as "catch-alls" for other petroleum compounds with consideration of the PAHs in mind. However, GRO and DRO are indicator parameters for petroleum contamination and situations are likely where these are not adequate or appropriate.

The PAHs include more than a hundred compounds with fused benzene rings. They comprise a large family of compounds with a rather large range of toxic potency (IARC, 1983; Santodonato et al., 1981). PAHs are products of incomplete combustion and are components of petroleum. They are ubiquitous in the environment from both natural and anthropogenic sources. PAHs are seldom found separately in the environment; rather, they occur as complex mixtures of numerous compounds. The specific PAH compounds addressed in this guidance are shown in Table 1. While these compounds are likely to be the most common PAHs encountered at most sites (ATSDR, 1995a; 1995b), their inclusion does not imply that these are the only PAH compounds of concern. Additional PAH compounds may be of concern at some sites and these should be evaluated on a site-specific basis.

Previous approaches to developing soil cleanup levels for PAHs have typically assumed that all carcinogenic PAHs are equipotent to benzo[*a*]pyrene (BaP). It has become apparent in recent years that the equipotency approach results in an overestimation of the carcinogenic risks associated with PAHs (U.S. EPA, 1993; LaGoy and Quirk, 1994). The basis for establishing risk-based soil cleanup levels for "total PAHs" relies on assumptions regarding the composition of a PAH mixture combined with assumed equipotency with benzo[*a*]pyrene or toxic equivalency factors. Thus, cleanup levels for "total PAHs" are inherently site-specific and generic values tend to be overly conservative.

Development of Suggested Generic Soil Cleanup Levels for PAHs

The suggested generic soil cleanup levels for PAHs provided in this guidance were developed consistent with the methodology used in developing the generic RCLs in ch. NR 720, Wis. Adm. Code, and with the procedures outlined in s. NR 720.19(4)-(5), Wis. Adm. Code. The suggested generic residual contaminant levels (RCLs) for individual PAH compounds are shown in Table 1.

Table 1. – Suggested generic residual contaminant levels (RCLs) for PAH compounds in soil (mg/kg)

Compound	CAS #	Groundwater Pathway	Direct Contact Pathway: Non-industrial	Direct Contact Pathway: Industrial
acenaphthene	83-32-9	38	900	60000
acenaphthylene	208-96-8	0.7	18	360
anthracene	120-12-7	3000	5000	300000
benz[*a*]anthracene	56-55-3	17	0.088	3.9
benzo[*a*]pyrene	50-32-8	48	0.0088	0.39
benzo[*b*]fluoranthene	205-99-2	360	0.088	3.9
benzo[*ghi*]perylene	191-24-2	6800	1.8	39
benzo[*k*]fluoranthene	207-08-9	870	0.88	39
chrysene	218-01-9	37	8.8	390
dibenz[*ah*]anthracene	53-70-3	38	0.0088	0.39
fluoranthene	206-44-0	500	600	40000
fluorene	86-73-7	100	600	40000
indeno[123-*cd*]pyrene	193-39-5	680	0.088	3.9
1-methyl naphthalene	90-12-0	23	1100	70000
2-methyl naphthalene	91-57-6	20	600	40000
naphthalene	91-20-3	0.4	20	110
phenanthrene	85-01-8	1.8	18	390
pyrene	129-00-00	8700	500	30000

Toxicological Basis

The commonly occurring PAHs are routinely subdivided into the "carcinogenic" and "noncarcinogenic" PAHs. Seven of the PAHs -- benzo[*a*]anthracene, benzo[*a*]pyrene, benzo[*b*]fluoranthene, benzo[*k*]fluoranthene, chrysene, dibenz[*ah*]anthracene, and indeno[123-*cd*]pyrene -- are classified as B2, probable human carcinogens, under U.S. EPA's weight of evidence classification system (U.S. EPA, 1997). The remaining PAHs addressed in this guidance are classified as D, not classifiable as to human carcinogenicity (U.S. EPA, 1997).

A cancer slope factor has only been established for benzo[*a*]pyrene (U.S. EPA, 1997; Smith, 1996). Several authors have evaluated the available data on the carcinogenic potency of different PAHs and developed toxicity equivalency factors (TEFs) for the individual PAHs (Clement Assoc., 1988; Nisbet and LaGoy, 1992; U.S. EPA, 1993). These TEFs are more properly termed estimated relative potency factors (RPFs) and indicate the carcinogenic potency of each compound relative to benzo[*a*]pyrene. Multiplying the RPF of each PAH by the cancer slope factor for benzo[*a*]pyrene can provide an estimated cancer slope factor for each compound.

Table 2 shows the RfDs and cancer slope factors used in development of the suggested generic RCLs for PAHs. The suggested generic soil cleanup levels for PAHs were developed using accepted reference doses (RfDs) or minimal risk levels (MRLs) for "noncarcinogenic" PAHs where such values are available (U.S. EPA, 1997; Anderson et al, 1992; ATSDR, 1995a; 1995b). Suggested soil cleanup levels for "carcinogenic" PAHs were developed based on the estimated relative potency factors (RPFs) of U.S. EPA (1993) relative to the cancer slope factors for benzo[*a*]pyrene (U.S. EPA, 1997; Smith, 1996). Cancer slope factors for the "carcinogenic" PAHs were calculated by multiplying the slope factors for benzo[*a*]pyrene by the estimated relative potency factor (RPF) for the compound. For the "noncarcinogenic" PAHs that lack an established reference dose (RfD) or minimal risk level (MRL), cancer slope factors were determined using the RPFs of Nisbet and LaGoy (1992). This use of the RPF approach is thought to be appropriate, in the absence of another toxicity index upon which to base a soil

Table 2. – Relative potency factors, estimated cancer slope factors, oral reference doses, and inhalation reference concentrations for individual PAH compounds

Compound	CAS #	RPF [a]	CSFo [b] (mg/kg-d)$^{-1}$	CSFi [c] (mg/kg-d)$^{-1}$	RfD [d] (mg/kg-d)	RfC [e] (mg/m^3)	Class [f]
acenaphthene	83-32-9	0.001			$6x10^{-2}$	na	D
acenaphthylene	208-96-8	0.001	$7.3x10^{-3}$	$6.1x10^{-3}$	na	na	D
anthracene	120-12-7	0.01			$3x10^{-1}$	na	D
benz[*a*]anthracene	56-55-3	0.1	$7.3x10^{-1}$	$6.1x10^{-1}$			B2
benzo[*a*]pyrene	50-32-8	1	7.3	6.1			B2
benzo[*b*]fluoranthene	205-99-2	0.1	$7.3x10^{-1}$	$6.1x10^{-1}$			B2
benzo[*ghi*]perylene	191-24-2	0.01	$7.3x10^{-2}$	$6.1x10^{-2}$	na	na	D
benzo[*k*]fluoranthene	207-08-9	0.01	$7.3x10^{-2}$	$6.1x10^{-2}$			B2
chrysene	218-01-9	0.001	$7.3x10^{-3}$	$6.1x10^{-3}$			B2
dibenz[*ah*]anthracene	53-70-3	1	7.3	6.1			B2
fluoranthene	206-44-0	0.001			$4x10^{-2}$	na	D
fluorene	86-73-7	0.001			$4x10^{-2}$	na	D
indeno[123-*cd*]pyrene	193-39-5	0.1	$7.3x10^{-1}$	$6.1x10^{-1}$			B2
1-methyl naphthalene	90-12-0	0.001			$7x10^{-2}$	na	D
2-methyl naphthalene	91-57-6	0.001			$4x10^{-2}$	na	D
naphthalene	91-20-3	0.001			$4x10^{-3}$	$2x10^{-3}$	D
phenanthrene	85-01-8	0.001	$7.3x10^{-3}$	$6.1x10^{-3}$	na	na	D
pyrene	129-00-00	0.001			$3x10^{-2}$	na	D

[a] Estimated relative potency factor

na = not available

[b] Oral cancer slope factor

[c] Inhalation cancer slope factor

[d] Oral reference dose (EPA/WDHS) or minimal risk level for oral exposure (ATSDR)

[e] Reference concentration (EPA) or minimal risk level for inhalation exposure (ATSDR)

[f] U.S. EPA weight-of-evidence classification for carcinogenicity

cleanup level, because evidence exists that these compounds may exhibit co-carcinogenic effects in mixtures and are mutagenic (ATSDR, 1995b; Nisbet and LaGoy, 1992; EPA, 1997; Anderson et al, 1996). Also, the soil cleanup levels generated by using these values are unlikely to underestimate the potential human health risk associated with these compounds.

Generic RCLs based on Direct Contact

The suggested generic RCLs based on direct contact with contaminated soil through ingestion and through inhalation in Table 1 were developed using the risk-based algorithms and default exposure assumptions used in ch. NR 720, Wis. Adm. Code, with the additional consideration of inhalation of volatiles. Toxicity indices used are shown in Table 2 and summary calculations are provided in Attachment A. The risk-based algorithms and exposure factors used are provided in Attachment B. The suggested generic RCLs for non-industrial (residential) scenario are based on a target risk of 1×10^{-7} or a hazard quotient of 0.2, consistent with those in s. NR 720.11, Wis. Adm. Code. As provided is s. NR 720.19(5)(a), Wis. Adm. Code, these values can be adjusted on a site-specific basis to a target risk of 1×10^{-6} or a hazard quotient of 1.

Generic RCLs based on Protection of Groundwater Quality

The suggested generic RCLs based on protection of groundwater quality in Table 1 were developed by using equilibrium soil:water partitioning to estimate soil moisture concentrations in the unsaturated zone, combined with a modification of the generic dilution-attenuation factor calculation used for the generic RCLs in Table 1 of ch. NR 720, Wis. Adm. Code. Parameter values used and summary calculations are provided in Attachment A. The methodology used is explained in Attachment C.

Target groundwater concentrations for development of the suggested generic RCLs are based on: 1) NR 140 preventive action limits (PALs), 2) proposed PALs developed by the Department of Health and Social Services (DHSS), or 3) PAL-equivalent risk-based concentrations. Groundwater standards are presently available in ch. NR 140, Wis. Adm. Code, for three of the PAHs - benzo[*a*]pyrene, naphthalene, and fluorene. In addition, DHSS has proposed draft groundwater standards for six additional PAHs - acenaphthylene, anthracene, benzo[*b*]fluoranthene, chrysene, fluoranthene, and pyrene (Anderson et al, 1996). For the remaining PAH compounds, risk-based concentrations equivalent to a preventive action limit were calculated (see Attachment C).

Alternative Approaches for Determining PAH Soil Cleanup Levels

Alternatives to the direct use of the suggested generic RCLs for individual PAHs may be appropriate and acceptable in some cases. These alternative approaches include the development of soil cleanup levels based on benzo[*a*]pyrene-equivalent concentrations and the application of soil cleanup levels for “total PAHs.”

Both of these approaches may be suitable in cases where the pathway of concern is restricted to protection of human health from direct contact. Such “lumped parameter” approaches are *not* appropriate for protection of groundwater quality because the leaching potential for each PAH compound is specific to that compound and they cannot be considered as a group. Typically, the “carcinogenic” PAHs do not readily leach and, except for acenaphthylene, the methyl naphthalenes, and naphthalene, the PAH compounds are likely to be only of concern for direct contact with contaminated soil in many cases. However, the migration to groundwater pathway should be evaluated separately.

Benzo[a]pyrene-Equivalent Concentrations

This approach may be used to advantage in some situations where the PAH mixture is dominated by the "carcinogenic" PAHs. Where only one or two of the PAHs are present in significant concentrations, the use of the suggested generic RCLs based on direct contact in Table 1 can result in a cleanup action being undertaken where the cumulative risk for the PAH mixture may not really warrant it. An example of this approach is provided in Attachment D.

The application of the benzo[*a*]pyrene-equivalent concentration approach involves conversion of the measured concentrations of PAH compounds to an equivalent concentration (with regard to toxic potency) of benzo[*a*]pyrene. The RPFs in Table 2 indicate the carcinogenic potency of each compound compared with benzo[*a*]pyrene. Multiplying the concentration of each PAH by its RPF and summing the resultant concentrations yields a concentration for the total PAH mixture expressed as an equivalent concentration of benzo[*a*]pyrene, called a benzo[*a*]pyrene-equivalent concentration (BaP_{equiv}).

Soil cleanup levels based on benzo[*a*]pyrene-equivalent concentrations are then developed using the risk-based algorithms for carcinogenic compounds in Attachment B and the cancer slope factor for benzo[*a*]pyrene (7.3 $(mg/kg\text{-}d)^{-1}$). However, in calculating soil cleanup levels for benzo[*a*]pyrene-equivalent concentrations, distributing the target risk equally among the PAH compounds and using a combined target excess cancer risk level is appropriate. This is conceptually consistent with the intent of the target risk requirements of ss. NR 720.11(3) and 720.19(5), Wis. Adm. Code, where risks are presumed to be additive and is appropriate here due to the underlying assumption of toxic potency for the other PAHs relative to benzo[*a*]pyrene. A combined target cancer risk level can be determined for the carcinogenic PAHs alone or for all the detected PAHs, up to the cumulative excess cancer risk limit of 1×10^{-5} specified in s. NR 720.11(3), Wis. Adm. Code.

The combined target excess cancer risk level is determined by multiplying the target risk for individual compounds by the number of compounds in the assessment. The generic RCLs in Table 2 of ch. NR 720, Wis. Adm. Code, are based on a target excess cancer risk for individual compounds of 1×10^{-7} for the nonindustrial (residential) scenario and 1×10^{-6} for the industrial scenario. The target risk for the nonindustrial scenario can be modified for *in situ* contaminated soil to 1×10^{-6} on a site-specific basis under s. NR 720.19(5)(a), Wis. Adm. Code. This distinction is important because soil cleanup levels equivalent to the generic RCLs are applicable to unrestricted off-site disposal under s. NR 718.14, Wis. Adm. Code.

Total PAHs

A similar approach can also be used to determine soil cleanup levels for "total PAHs" if the assumption is made that measured total PAH concentration represents a benzo[*a*]pyrene-equivalent concentration and that all the PAHs are present. This assessment would involve all 18 compounds and use a combined target excess cancer risk level of 1.8×10^{-6} for the non-industrial (residential) scenario and 1×10^{-5} for the industrial scenario. The resultant soil cleanup levels for "total PAHs" equivalent to the generic RCLs would be 3.9 mg/kg for the industrial exposure scenario and 0.16 mg/kg for the non-industrial (residential) exposure scenario. Again, the value for the non-industrial scenario can be modified for *in situ* contaminated soil using a combined target risk of 1×10^{-5} to 0.9 mg/kg on a site-specific basis.

This approach can be useful for dealing with treatment residuals. It is inherently conservative since the resulting generic RCLs are compared directly to measured total PAH concentrations.

Qualifications and Considerations for Applying Suggested PAH Soil Cleanup Levels

A variety of qualifications and considerations are involved in use of the suggested PAH soil cleanup levels included in this guidance. The suggested generic soil cleanup levels presented in this guidance are expected to be adequate and appropriate at most sites. If used properly, they should not result in overly conservative cleanups. However, **the availability of suggested generic soil cleanup levels for PAHs should not be construed to preclude site-specific decisionmaking**. Substantially higher levels could be allowable and appropriate if supported by a site-specific evaluation under s. NR 720.19, Wis. Adm. Code. A consideration of these issues is critical to defining the risk posed by PAHs at hazardous substance discharge sites.

Background Concentrations of PAHs

PAHs are widespread in the environment from both natural and anthropogenic sources (Menzie et al, 1992; IARC, 1983). Background concentrations of PAH compounds resulting from atmospheric deposition may be significantly elevated in some surface soils, particularly in urban areas and along roadways. The generic RCLs are not intended to require cleanup to below existing background concentrations at a site. Background concentrations should be considered, as provided in s. NR 720.11(5), Wis. Adm. Code. PAH compounds do not readily leach and background concentrations in subsoil can be expected to be *significantly* lower than those in surface soils. Elevated PAH concentrations at depth are typically associated with a release or waste material and are not "background." For comparision to background, the samples should be taken from a similar depth.

Background concentrations should be determined in the immediate vicinity of the site, but away from areas likely to be affected by a hazardous substance discharge involving PAHs. Sample locations likely to bias estimates of background concentrations should be avoided, such as around creosote-treated posts or telephone poles or immediately adjacent to asphalt surfaces. Direct comparison of elevated background concentrations of PAHs in surface soils to PAH concentrations occurring at depth in subsoils is <u>not</u> appropriate, since PAH concentrations in surface soil bear no direct relation to those in subsoils. The presence of PAH-contaminated soil at depth that is above background concentrations does not necessarily require that a cleanup action be done since the potential for exposure may not currently exist. Such situations could constitute a performance standard under s. NR 720.19(2), Wis. Adm. Code, where the "standard of performance" is that a soil cap of appropriate thickness is present and maintained so that no exposure is occurring. However, an institutional control, such as a deed restriction or deed affadavit, may be necessary to prevent excavation, or to minimize future exposure if the contaminated soil is brought to the surface and to ensure that it is managed properly. Also, the presence of a soil "cap" does not necessarily address inhalation of volatiles since volatilization to the atmosphere can occur from soils at depth and must be considered.

Comparisons between background concentrations and contaminant concentrations should be based on comparison of the sampled populations for the site. Sampling for comparisons to background is discussed below. Comparison of contaminant concentrations to maximum point values for background PAH concentrations can produce biased estimates and are not relevant to exposure concentrations. Similarly, the use of arbitrary statistical measures for background concentrations (e.g., mean plus three standard deviations) is not appropriate.

Pathways Not Considered

The suggested generic RCLs contained in this guidance apply to soil contamination in the unsaturated zone. They address protection of human health from direct contact through ingestion, inhalation of volatiles and soil particulates, and protection of groundwater quality from leaching. The suggested RCLs based on direct contact can also be used for soil contamination in the saturated zone, as discussed below. They do *not* address potential surface water and sediment impacts from surface runoff and washload transport. These additional pathways should be evaluated on a site-specific basis where they are of concern, such as at many coal gas sites.

In addition, the suggested generic RCLs for protection of human health from direct contact with contaminated soil do not include consideration of dermal contact. Evidence exists to indicate that dermal contact may be a significant exposure pathway (ATSDR, 1995b) and a preliminary evaluation of site-of-contact risks associated with dermal exposure suggests that this could drive cleanups at some sites (LaGoy and Quirk, 1994). Therefore, dermal contact should be considered at sites where there is likelihood of significant exposure via this route. Approaches for evaluating dermal contact can be found in U.S. EPA (1992a).

The suggested soil cleanup levels for PAHs included in this guidance are *not* intended as cleanup criteria for contaminated sediment and should not be used as such.

Contaminated Soil at or Near the Water Table

In cases where PAH-contaminated "soil" lies near or below the water table where it is directly in contact with groundwater during all or part of the year, the use of the suggested generic RCLs based on protection of groundwater quality is inappropriate. In such cases the potential groundwater impacts should be evaluated directly through groundwater sampling. Groundwater samples should be taken at a time when the contaminated soil is below the water table.

At sites where depth to groundwater is only a few feet, the direct contact pathway is still of concern even where leaching to groundwater may not be an issue. While contaminated soil below the water table is not "soil" as defined in ch. NR720, Wis. Adm. Code, it is a contaminated media that must be addressed. The RCLs for direct contact are as appropriate for saturated soil as for soil in the unsaturated zone. As noted previously, the presence of PAH contaminated soil at depth does not necessarily require that a cleanup action be done since the potential for exposure may not currently exist. However, an institutional control, such as a deed restriction or deed affadavit, may be necessary to prevent excavation, or to minimize future exposure if the contaminated soil is brought to the surface and to ensure that it is managed properly.

Relationship to Generic RCLs for GRO/DRO

The generic soil cleanup levels for gasoline range organics (GRO) and diesel range organics (DRO) contained in s. NR 720.09(4), Wis. Adm. Code, were specifically included as "catch-alls" for other petroleum compounds, including PAHs. They are intended to be used for sites with contamination from *petroleum* where RCLs for other specific compounds are not available or not developed. However, GRO and DRO are merely indicator parameters for petroleum contamination and are measures of the total hydrocarbon concentration in a given range (C_5-C_{10} for GRO and C_{10}-C_{28} for DRO). For soil contamination other than from petroleum, the generic GRO/DRO soil cleanup levels are likely not adequate or appropriate since they do not provide information on the identity of the hydrocarbon constituents.

If needed, site-specific soil cleanup levels for GRO and DRO can be developed using surrogate compound approaches such as those presented in Heath et al (1993) and Magee et al (1993). The constituents of concern in petroleum products useful as surrogates include the BTEX compounds, MTBE, *n*-hexane, the trimethylbenzenes, and the PAHs. However, this approach requires development of RCLs for the individual surrogate compounds which can be used directly.

The PAH compounds addressed in this guidance are in the range C_{10}-C_{22} and, with the trimethylbenzenes, constitute the major constituents of concern in the DRO range for petroleum. If compound-specific RCLs are used for all these constituents of concern, the additional application of an RCL for DRO is redundant and it can be disregarded. A more practical concern is that samples containing more than 100 mg/kg GRO/DRO require dilution prior to analysis which can increase detection limits for individual compounds above acceptable levels.

Hazardous Waste Issues

The suggested generic soil cleanup levels for PAHs contained in this guidance are *not* intended to address whether soil contaminated with PAHs could be a characteristic hazardous waste as determined by the toxicity characteristic leaching procedure (TCLP). It is important to remember that the TCLP test (EPA Method 1311) is intended to represent leaching of a waste disposed of in a municipal solid waste landfill. While this is not particularly relevent to soil cleanup levels, it is possible that PAH-contaminated soils that meet applicable soil cleanup levels could still fail TCLP. This could be an issue at some sites, particularly for disposal of excavated soils.

Treatment Residuals

Treated soils that meet the suggested generic RCLs provided in Table 1 should be considered to meet the criteria that are required for unrestricted off-site disposal under s. NR 718.14, Wis. Adm. Code.

The presence and nature of PAHs as contaminants at a site should be determined during the site investigation. Since PAHs are products of incomplete combustion and pyrolysis, thermal treatment of contaminated soils can result in production of PAHs that were not originally present as contaminants at the site.

Toxicological Uncertainty

Recent reviews of the toxicological information on the PAH compounds addressed in this guidance can be found in ATSDR toxicological profiles (ATSDR, 1995a; 1995b).

In calculating site risks, the PAHs historically have been separated into two categories: carcinogens and noncarcinogens, and all the carcinogenic PAHs treated as equipotent with benzo[*a*]pyrene, one of the more potent PAHs. This approach oversimplifies the situation, as some of the “carcinogenic” compounds are clearly more potent than others, and some of the “noncarcinogenic” compounds appear to have some weak carcinogenic activity or to act as cancer promoters or cocarcinogens (ATSDR, 1995b; Santodonato et al., 1981; Nisbet and LaGoy, 1992).

Issues related to regulatory toxicology that affect uncertainty in risk estimates for PAHs include the lack of a dose-response estimate for site-of-contact tumors caused by dermal exposure, questions regarding the accuracy of the available cancer slope factor for oral exposure, and the lack of an adequate approach for addressing the potency of mixtures of PAHs (LaGoy and Quirk, 1994). Toxic interactions among the PAHs are complex and no broadly applicable, consistent approach has been developed. The toxicological data base on PAHs is insufficient to support the development of cancer slope factors for individual PAH compounds other than benzo[*a*]pyrene (ATSDR, 1995b; U.S. EPA, 1993). The estimated relative potency approach used in this guidance does not meet all of the requirements necessary for the development of toxic equivalency factors (TEFs) similar to those used for assessment of risks from dioxin-like compounds

(Nisbet and LaGoy, 1992; U.S. EPA, 1993).

Nisbet and LaGoy (1992) and U.S. EPA (1993) evaluated several relative potency approaches for PAHs and presented modified versions that differ minimally. Nisbet and LaGoy (1992) suggest a relative potency of 0.01 for chrysene as compared with the EPA's value of 0.001. Additionally, this study considers a relative potency of five (5) more likely for dibenz[*ah*]anthracene at the low doses expected to be encountered in the natural environment; EPA recommends a relative potency of one (1) for dibenz[*ah*]anthracene. Nisbet and LaGoy (1992) also suggest that many PAHs now thought to be noncarcinogenic may in fact show some potency in mixtures and provide relative potency factors for these compounds. This possibility has been explored by other researchers, however, quantitative estimates are equivocal (ATSDR, 1995b) and insufficient evidence is available to classify these compounds as B2 carcinogens.

Other factors that affect uncertainty in exposure estimates include questions regarding the effect of the environmental matrix on the availability of the chemicals to a biological receptor and the lack of information on levels of those PAHs that are not detected using standard analytical procedures (LaGoy and Quirk, 1994). Where relevent data is available for a site, consideration of bioavailability is appropriate. The standard analytical methods used for PAHs (EPA methods 8310 and 8270) test for the presence of only 18 of the many PAHs likely to occur in environmental samples. While the PAHs that are analyzed in the standard EPA procedures may pose a substantial portion of the risk in most materials (ATSDR, 1995b), the other PAHs may contribute to risk at PAH-contaminated sites. It is likely that a significant percentage of the PAHs would be routinely overlooked and consequently not considered in risk estimates (LaGoy and Quirk, 1994). Furthermore, certain methylated PAHs and PAHs containing nitrogen or oxygen may be quite potent carcinogens and if present could pose substantial risks (Santodonato et al., 1981; IARC, 1983; ATSDR, 1995b).

Sampling for Comparison to Soil Cleanup Levels

The following discussion is intended to highlight considerations for sampling for comparision to soil cleanup levels rather than to provide detailed guidance since these issues have broad application beyond the PAHs. Sources of additional information are provided and more detailed guidance on this subject will be available in the future.

Samples to determine the nature, degree, and extent of PAH contamination in soils should be collected during the site investigation phase at all sites where PAHs may be contaminants of concern due to the nature of the release. Site investigation soil samples must be discrete samples taken and handled in accordance with s. NR 716.13, Wis. Adm. Code. Subsequent soil sampling at the site may be modified for specific considerations.

When measured concentrations in soil are compared to RCLs, it is important to consider the basis for the RCL and what it is intended to protect. In all cases, measured concentrations from individual soil samples can be compared directly to the RCLs. However, in some cases this can result in soil cleanup actions being undertaken that may not be warranted by the pathway of concern.

Sampling for the Direct Contact Pathway

The generic RCLs for protection of human health from direct contact with contaminated soil are based on chronic (long term) exposure. Chronic exposure to site contaminants is best represented by an arithmetic average concentration for an exposure area (U.S. EPA, 1992b). While point contaminant concentrations from individual discrete samples can be used for comparision to the RCLs, they are not necessarily relevant to exposure concentrations. Average measured soil concentrations are best represented by the upper 95% confidence limit on the arithmetic mean of the concentrations in individual samples. To be considered below the RCL, the upper 95% confidence limit on the arithmetic mean of the sampled contaminant concentrations should be less than the RCL. The method for calculating the upper 95% confidence limit on the mean can be found in U.S. EPA (1989; 1992b) or in statistics texts (e.g., Gilbert, 1987).

Sampling for the Migration to Groundwater Pathway

The generic RCLs for protection of groundwater quality are based on soil concentrations that will not result in leaching that will cause a preventive action limit to be exceeded in groundwater. For the migration to groundwater pathway, soils that have constituents that may leach to produce a groundwater impact that exceeds NR 140 preventive action limits are of primary concern. Therefore, it is the *source areas* that are of interest; not necessarily an exposure area as discussed above for the direct contact pathway. Areal averaging of concentrations is inappropriate. To determine whether soil contaminants exceed the RCLs for the migration to groundwater pathway, measured concentrations from discrete samples at specific locations should be used.

Sampling for Comparison to Background Concentrations

The purpose of comparision to background concentrations is to determine whether or not the exposure concentration for contaminated soil at the site is higher than the exposure concentration due to background. Background concentrations are best represented by the upper 95% confidence limit on the arithmetic mean. To be considered below background concentrations, the upper 95% confidence limit on the arithmetic mean of the sampled contaminant concentrations should be less than or equal to that of the sampled background concentration. Some statistical approaches for evaluating comparisons to background concentrations are presented in Gilbert (1987), Liggett (1984), and Gilbert and Simpson (1990).

The number of samples needed for determination of background concentrations is a site-specific consideration. However, the results of population comparisons are strongly affected by the sample size. The use of composite samples for PAHs may be appropriate, both for determining background and contaminant concentrations, and can reduce the associated analytical costs. However, if composite samples are used the sample statistics must be adjusted appropriately (Gilbert, 1987). The use of composite samples is described further below.

Use of Composite Sampling for PAHs

Compositing of samples can be appropriate where the measurement of interest is the mean. Therefore, composite sampling has potential application for comparison of contaminant concentrations to RCLs based on direct contact or for comparison to background concentrations, since the physical “averaging” that occurs is consistent with the use of the data. While compositing of soil samples is not appropriate for volatile organic compounds (U.S. EPA, 1989; 1992b), most of the PAH compounds are not subject to volatile loss to any significant extent. Therefore, the use of composite samples can be acceptable for PAHs and can reduce analytical costs. However, the presence of low molecular weight PAHs, such as naphthalene, the methyl naphthalenes, acenaphthene, etc., that may be affected by volatile losses should be considered. Compositing of samples can be done either in the field or at the analytical laboratory and due care should be exercised in sample handling to prevent sample degradation. The use of a single composite sample should be avoided and if composite samples are used the sample statistics used for determining the upper 95% confidence limit on the mean must be adjusted appropriately (Gilbert, 1987). Other considerations for the appropriate use of composite samples are discussed in U.S EPA (1989; 1996).

Where to Go for Further Information

Additional information and discussion of specific topics can be found in the references cited in this guidance. Additional copies of this guidance can be obtained from the Department at: Public Information Requests, Wisconsin Department of Natural Resources, P.O. Box 7921, RR/3, Madison, WI 53707, or by calling (608) 264-6009. It can also be obtained in electronic format from the Bureau for Remediation & Redevelopment BBS via modem at (608) 261-6455 (8-N-1). A Microsoft Excel 5.0 spreadsheet containing values and calculations for the suggested generic RCLs presented in this guidance is also available on the BBS. Questions regarding this guidance should be directed to Michael J. Barden at (608) 264-6007.

Additional discussion and elaboration on some issues addressed in this guidance can be found in the following guidance documents which are also available from the address above:

- *Interim Guidance on Soil Performance Standards* -- PUBL RR-528-97
- *Interim guidance on the Use of Leaching Tests for Unsaturated Soils to Determine Groundwater Contamination Potential* -- PUBL RR-523-97

This guidance will be updated as needed. Comments and suggestions can be sent to Guidance Updates, attn. Dale Zeige, at the address above.

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Attachment A

Summary Calculations for Suggested Generic RCLs

direct contact

Compound	CAS #		RfDo	RfC	CSFo	CSFi	Class	non-industrial non-cancer ingest	non-industrial non-cancer inhal	non-industrial cancer ingest	non-industrial cancer inhal	industrial non-cancer ingest	industrial non-cancer inhal	industrial cancer ingest	industrial cancer inhal	RCL (mg/kg) non-industrial	RCL (mg/kg) industrial
acenaphthene	83-32-9		6e-02	na			D	900	nd			60000	nd			900	60000
acenaphthylene	208-96-8		na	na	7.3e-03	6.1e-03	D			18	51			390	360	18	360
anthracene	120-12-7		3e-01	na			D	5000	nd			300000	nd			5000	300000
benz(a)anthracene	56-55-3				7.3e-01	6.1e-01	B2			0.088	11			3.9	150	0.088	3.9
benzo(a)pyrene	50-32-8				7.3e+00	6.1e+00	B2			0.0088	1.6			0.39	22	0.0088	0.39
benzo(b)fluoranthene	205-99-2				7.3e-01	6.1e-01	B2			0.088	4.6			3.9	65	0.088	3.9
benzo(ghi)perylene	191-24-2		na	na	7.3e-02	6.1e-02	D			1.8	1100			39	7700	1.8	39
benzo(k)fluoranthene	207-08-9				7.3e-02	6.1e-02	B2			0.88	380			39	5300	0.88	39
chrysene	218-01-9				7.3e-03	6.1e-03	B2			8.8	270			390	3800	8.8	390
dibenz(ah)anthracene	53-70-3	high			7.3e+00	6.1e+00	B2			0.0088	7.8			0.39	110	0.0088	0.39
		low			3.7e+01	3.1e+01	B2			0.0018	1.6			0.078	22	0.0018	0.078
fluoranthene	206-44-0		4e-02	na			D	600	nd			40000	nd			600	40000
fluorene	86-73-7		4e-02	na			D	600	nd			40000	nd			600	40000
indeno(123-cd)pyrene	193-39-5				7.3e-01	6.1e-01	B2			0.088	54			3.9	750	0.088	3.9
1-methyl naphthalene			7e-02	na			D	1100	nd			70000	nd			1100	70000
2-methyl naphthalene	91-57-6		4e-02	na			D	600	nd			40000	nd			600	40000
naphthalene	91-20-3		4e-03	2e-03			D	60	20			4000	110			20	110
phenanthrene	85-01-8		na	na	7.3e-03	6.1e-03	D			18	160			390	1100	18	390
pyrene	129-00-00		3e-02	na			D	500	nd			30000	nd			500	30000

na = not available

nd = not determined

groundwater

Compound	CAS #	RfD	CSF	Class	Risk (ug/L)	ES (ug/L)	PAL (ug/L)	NR 140?	Koc	DAF	RCL (mg/kg)
acenaphthene	83-32-9	6e-02		D	600	600	120		2.46e+03	1.23e+02	38
acenaphthylene	208-96-8	na	7.3e-03	D	4.8	5	1	p	3.68e+03	1.79e+02	0.7
anthracene	120-12-7	3e-01		D	3000	3000	600	p	1.10e+04	5.06e+02	3000
benz(a)anthracene	56-55-3		7.3e-01	B2	0.048	0.048	0.0048		2.77e+05	1.25e+04	17
benzo(a)pyrene	50-32-8		7.3e+00	B2	0.0048	0.2	0.02	y	2.31e+05	1.04e+04	48
benzo(b)fluoranthene	205-99-2		7.3e-01	B2	0.048	0.2	0.02	p	6.33e+05	2.85e+04	360
benzo(ghi)perylene	191-24-2	na	7.3e-02	D	0.48	0.48	0.096		1.26e+06	5.65e+04	6800
benzo(k)fluoranthene	207-08-9		7.3e-02	B2	0.48	0.48	0.048		6.33e+05	2.85e+04	870
chrysene	218-01-9		7.3e-03	B2	4.8	0.2	0.02	p	2.01e+05	9.08e+03	37
dibenz(ah)anthracene	53-70-3		7.3e+00	B2	0.0048	0.0048	0.00048		1.33e+06	5.98e+04	38
fluoranthene	206-44-0	4e-02		D	400	400	80	p	1.10e+04	5.09e+02	500
fluorene	86-73-7	4e-02		D	400	400	80	y	5.03e+03	2.39e+02	100
indeno(123-cd)pyrene	193-39-5		7.3e-01	B2	0.048	0.048	0.0048		1.77e+06	7.96e+04	680
1-methyl naphthalene		7e-02		D	700	700	140		1.71e+03	8.97e+01	23
2-methyl naphthalene	91-57-6	4e-02		D	400	400	80		1.87e+03	9.69e+01	20
naphthalene	91-20-3	4e-03		D	40	40	8	y	8.28e+02	5.02e+01	0.4
phenanthrene	85-01-8	na	7.3e-03	D	4.8	4.8	0.96		6.32e+03	2.97e+02	1.8
pyrene	129-00-00	3e-02		D	300	250	50	p	6.21e+04	2.81e+03	8700

y = included in NR 140

p = proposed for inclusion in NR 140

Attachment B

Risk-Based Algorithms for RCLs Based on Direct Contact

The risk-based algorithms used in developing the suggested generic residual contaminant levels (RCLs) for the PAHs are provided below. They are the same algoritms used in the development of generic RCLs in Table 2 of ch. NR 720, Wis. Adm. Code, with the addition of consideration of inhalation of volatiles for the inhalation pathway. These algorithms back-calculate a soil concentration (RCL) from a target risk level (for carcinogens) or hazard quotient (for noncarcinogens). They are based on the methodology presented in RAGS HHEM, Part B (U.S. EPA, 1991) and updates to those methods presented in U.S. EPA (1996).

The default target hazard quotients for noncarcinogens and target excess cancer risk levels for carcinogens provided are those used for individual compounds in the development of generic RCLs in Table 2 of ch. NR 720, Wis. Adm. Code. The basis of these values for the non-industrial (residential) exposure scenarios is analogous to the derivation of preventive action limits (PALs) for groundwater. They are determined as a percentage of the target hazard quotient or target excess cancer risk used for the industrial exposure scenario; 20% for the noncarcinogens and class D carcinogens, and 10% for carcinogens. This effectively results in a target hazard quotient of 0.2 for noncarcinogens and a target excess cancer risk of $1{\times}10^{-7}$ for carcinogens. For the PAHs that are class D carcinogens where a cancer endpoint was used in developing the suggested generic RCLs, an excess target cancer risk of $2{\times}10^{-7}$ was used. These target levels can be modified on a site-specific basis for *in situ* soil contamination to a hazard quotient of one (1) and an excess cancer risk of $1{\times}10^{-6}$ as provided in s. NR 720.19(5)(a), Wis. Adm. Code.

Risk-Based Algorithms for Soil Ingestion

The default exposure factors used for direct ingestion of contaminated soil are those specified in s. NR 720.19(5)(c), Wis. Adm. Code. The values for non-industrial (residential) exposure are the same as the default values used by U.S. EPA in the soil screening level methodology (U.S. EPA, 1996).

Algorithm for Ingestion of Noncarcinogenic Contaminants in Non-Industrial (Residential) Soil Based on Childhood Exposure

$$\text{Residual Contaminant Level (mg/kg)} = \frac{\text{THQ} \times \text{BWc} \times \text{AT} \times 365\ \text{d/yr}}{1/\text{RfDo} \times 10^{-6}\ \text{kg/mg} \times \text{EF} \times \text{ED} \times \text{IRc}} \qquad (1)$$

Parameter/Definition (units)	Default
THQ/target hazard quotient (unitless)	0.2
BWc/average body weight for child (kg)	15
AT/averaging time (yr) [a]	6
RfDo/oral reference dose (mg/kg-d)	chemical-specific
EF/exposure frequency (d/yr)	350
ED/exposure duration (yr)	6

Parameter/Definition (units)	Default
IRc/soil ingestion rate for child (mg/d)	200

[a] For noncarcinogens, averaging time is equal to exposure duration.

Algorithm for Ingestion of Noncarcinogenic Contaminants in Industrial Soil

$$\text{Residual Contaminant Level (mg/kg)} = \frac{THQ \times BWa \times AT \times 365 \text{ d/yr}}{1/RfDo \times 10^{-6} \text{ kg/mg} \times EF \times ED \times IRa} \quad (2)$$

Parameter/Definition (units)	Default
THQ/target hazard quotient (unitless)	1
BWa/average body weight for adult (kg)	70
AT/averaging time (yr) [a]	25
RfDo/oral reference dose (mg/kg-d)	chemical-specific
EF/exposure frequency (d/yr)	250
ED/exposure duration (yr)	25
IRa/soil ingestion rate for adult (mg/d)	100

[a] For noncarcinogens, averaging time is equal to exposure duration.

Algorithm for Ingestion of Carcinogenic Contaminants in Non-Industrial (Residential) Soil

$$\text{Residual Contaminant Level (mg/kg)} = \frac{TR \times AT \times 365 \text{ d/yr}}{SFo \times 10^{-6} \text{ kg/mg} \times EF \times IFs} \quad (3)$$

where

$$IFs = \frac{IRc \times EDc}{BWc} + \frac{IRa \times EDa}{BWa} \quad (4)$$

Parameter/Definition (units)	Default
TR/target cancer risk level (unitless)	1×10^{-7}
AT/averaging time (yr)	70
SFo/oral cancer slope factor $(mg/kg\text{-}d)^{-1}$	chemical-specific
EF/exposure frequency (d/yr)	350
IFs/age-adjusted soil ingestion factor (mg-yr/kg-d)	114
IRc/ingestion rate of soil age 1-6 (mg/d)	200

Parameter/Definition (units)	Default
EDc/exposure duration during ages 1-6 (yr)	6
BWc/average body weight from ages 1-6 (kg)	15
IRa/ingestion rate of soil age 7-31 (mg/d)	100
EDa/exposure duration during ages 7-31 (yr)	24
BWa/average body weight from ages 7-31 (kg)	70

Algorithm for Ingestion of Carcinogenic Contaminants in Industrial Soil

$$\text{Residual Contaminant Level (mg/kg)} = \frac{TR \times BWa \times AT \times 365 \text{ d/yr}}{SFo \times 10^{-6} \text{ kg/mg} \times EF \times ED \times IRa} \quad (5)$$

Parameter/Definition (units)	Default
TR/target cancer risk level (unitless)	1×10^{-6}
BWa/average body weight for adult (kg)	70
AT/averaging time (yr)	70
SFo/oral cancer slope factor $(mg/kg\text{-}d)^{-1}$	chemical-specific
EF/exposure frequency (d/yr)	250
ED/exposure duration (yr)	25
IRa/soil ingestion rate for adult (mg/d)	100

Risk-Based Algorithms for Inhalation Exposure

The algorithms for the inhalation pathway include consideration of inhalation of volatiles and inhalation of particulate matter. The default exposure factors used for the inhalation pathway are those specified in s. NR 720.19(5)(c), Wis. Adm. Code. The values for non-industrial exposure are the same as the default values used by U.S. EPA in the soil screening level methodology (U.S. EPA, 1996), with the exception of the particulate emission factor (PEF). The soil-to-air volatilization factor is described below.

The algorithms for industrial exposure include a correction factor to adjust the inhalation rate to 24 m^3/d as specified in s. NR 720.19(5)(c), Wis. Adm. Code. Also, the algorithms for inhalation of carcinogenic contaminants are written in terms of the inhalation cancer slope factor (CFS_i) rather than the inhalation unit risk factor (URF) since only CFS_is were available for the PAHs. The algorithms should be appropriately modified if used with URFs (see U.S. EPA, 1996).

Algorithm for Inhalation of Noncarcinogenic Contaminants from Non-Industrial (Residential) Soil

$$\text{Residual Contaminant Level (mg/kg)} = \frac{\text{THQ} \times \text{AT} \times 365\ \text{d/yr}}{\frac{1}{\text{RfC}} \times \text{EF} \times \text{ED} \times \left[\left(\frac{1}{\text{VF}}\right) + \left(\text{Cp} \times 10^{-9}\ \text{kg}/\mu\text{g}\right)\right]} \qquad (6)$$

Parameter/Definition (units)	Default
THQ/target hazard quotient (unitless)	0.2
AT/averaging time (yr) [a]	30
RfC/reference concentration (mg/m^3)	chemical specific
EF/exposure frequency (d/yr)	350
ED/exposure duration (yr)	30
VF/volatilization factor (kg/m^3)	chemical specific
Cp/concentration of particulates less than 10 µm in air ($\mu g/m^3$) [b]	1.4

[a] For noncarcinogens, averaging time is equal to exposure duration.
[b] The quantity Cp × 10^{-9} kg/µg is equivalent to the term 1/PEF in U.S. EPA (1996)

Algorithm for Inhalation of Noncarcinogenic Contaminants from Industrial Soil

$$\text{Residual Contaminant Level (mg/kg)} = \frac{\text{THQ} \times \text{AT} \times 365\ \text{d/yr}}{\frac{1}{\text{RfC}} \times \text{EF} \times \text{ED} \times \text{IRc} \times \left[\left(\frac{1}{\text{VF}}\right) + \left(\text{Cp} \times 10^{-9}\ \text{kg}/\mu\text{g}\right)\right]} \qquad (7)$$

Parameter/Definition (units)	Default
THQ/target hazard quotient (unitless)	1
AT/averaging time (yr) [a]	25
RfC/reference concentration (mg/m^3)	chemical specific
EF/exposure frequency (d/yr)	250
ED/exposure duration (yr)	25
IRc/inhalation rate correction for adult laborer (unitless)	1.2
VF/volatilization factor (kg/m^3)	chemical specific
Cp/concentration of particulates less than 10 µm in air ($\mu g/m^3$) [b]	1.4

[a] For noncarcinogens, averaging time is equal to exposure duration.
[b] The quantity Cp × 10^{-9} kg/µg is equivalent to the term 1/PEF in U.S. EPA (1996)

Algorithm for Inhalation of Carcinogenic Contaminants from Non-Industrial (Residential) Soil

$$\text{Residual Contaminant Level (mg/kg)} = \frac{TR \times BWa \times AT \times 365\ \text{d/yr}}{SFi \times EF \times ED \times IR \times \left[\left(\frac{1}{VF}\right) + \left(Cp \times 10^{-9}\ \text{kg}/\mu\text{g}\right)\right]} \qquad (8)$$

Parameter/Definition (units)	Default
TR/target cancer risk level (unitless)	1×10^{-7}
BWa/average body weight for adult (kg)	70
AT/averaging time (yr)	70
SFi/inhalation cancer slope factor $(mg/kg\text{-}d)^{-1}$	chemical specific
EF/exposure frequency (d/yr)	350
ED/exposure duration (yr)	30
IR/inhalation rate (m^3/d)	20
VF/volatilization factor (kg/m^3)	chemical specific
Cp/concentration of particulates less than 10 µm in air (µg/m^3) [a]	1.4

[a] The quantity Cp × 10^{-9} kg/µg is equivalent to the term 1/PEF in U.S. EPA (1996)

Algorithm for Inhalation of Carcinogenic Contaminants from Industrial Soil

$$\text{Residual Contaminant Level (mg/kg)} = \frac{TR \times BWa \times AT \times 365\ \text{d/yr}}{SFi \times EF \times ED \times IRw \times \left[\left(\frac{1}{VF}\right) + \left(Cp \times 10^{-9}\ \text{kg}/\mu\text{g}\right)\right]} \qquad (9)$$

Parameter/Definition (units)	Default
TR/target cancer risk level (unitless)	1×10^{-6}
BWa/average body weight for adult (kg)	70
AT/averaging time (yr)	70
SFi/inhalation cancer slope factor $(mg/kg\text{-}d)^{-1}$	chemical specific
EF/exposure frequency (d/yr)	250
ED/exposure duration (yr)	25
IRw/inhalation rate for adult laborer (m^3/d)	24
VF/volatilization factor (kg/m^3)	chemical specific

Parameter/Definition (units)	Default
Cp/concentration of particulates less than 10 µm in air (µg/m^3) [a]	1.4

[a] The quantity Cp × 10^{-9} kg/µg is equivalent to the term 1/PEF in U.S. EPA (1996)

Volatilization Factor

The soil-to-air volatilization factor (VF) is used to relate the concentration of the contaminant in soil to the flux of the contaminant in the vapor phase to the atmosphere. The volatilization factor (VF) equation presented here is based on the infinite source volatilization model of Jury et al. (1983; 1984). This equation and the default parameter values are taken from U.S. EPA (1996).

$$\mathrm{VF}\ (\mathrm{m}^3/\mathrm{kg}) = Q/C \times \frac{(3.14 \times D_A \times T)^{\frac{1}{2}}}{2 \times \rho_b \times D_A} \times 10^{-4}\ (\mathrm{m}^2/\mathrm{cm}^2) \tag{10}$$

where

$$D_A = \frac{\left[\left(\theta_a^{\frac{10}{3}} D_a H' + \theta_w^{\frac{10}{3}} D_w\right) \times \frac{1}{n^2}\right]}{\rho_b K_d + \theta_w + \theta_a H'} \tag{11}$$

Parameter/Definition (units)	Default
VF/volatilization factor (kg/m^3)	--
Q/C/inverse of the mean concentration at center of square source ((g/m^2-s)/(kg/m^3))	68.81
D_A/apparent diffusivity (cm^2/s)	--
T/exposure interval (s)	9.5×10^8
ρ_b/soil dry bulk density (g/cm^3)	1.5
θ_a/air-filled porosity (cm^3/cm^3)	0.28
D_a/air diffusion coefficient (cm^2/s)	chemical-specific
H′/dimensionless Henry's law constant (unitless)	chemical-specific
θ_w/volumetric soil moisture content (cm^3/cm^3)	0.15
D_w/water diffusion coefficient (cm^2/s)	chemical-specific
n/total soil porosity (cm^3/cm^3)	0.43
K_d/soil:water distribution coefficient (L/kg)	$= K_{oc} \times f_{oc}$
K_{oc}/organic carbon:water partitioning coefficient (L/kg)	chemical-specific
f_{oc}/soil organic carbon content (g/g)	0.006

The infinite source volatilization model is used for determination of generic RCLs because the mass limitations associated with a finite source model are inherently site-specific and cannot be handled in a generic fashion. The infinite source model (Jury et al., 1983; 1984) is consistent with the finite source volatilization model of Jury et al. (1990), which can be used for development of site-specific RCLs that include consideration of mass limitations.

The chemical parameter values used for calculating the volatilization factor for the PAHs and the resulting values are summarized in Table B-1. Determination of values for the organic carbon:water partitioning coefficient (K_{oc}) is discussed in Attachment C. Values for the Henry's law constant (H) are taken from U.S. EPA (1996) or ATSDR (1995a; 1995b). Values for the air diffusion coefficient (D_a) and water diffusion coefficient (D_w) are taken from U.S. EPA (1996), except the values for acenaphthylene, benzo[*ghi*]perylene, the methyl naphthalenes, and phenanthrene were estimated from the values for acenaphthene, benzo[*a*]pyrene, naphthalene, and anthracene, respectively, using the following relationship (Lyman et al., 1990):

$$\frac{D_1}{D_2} = \sqrt{\frac{MWT_2}{MWT_1}} \qquad (12)$$

where D_1 and D_2 are the diffusion coefficients and MWT_1 and MWT_2 are the molecular weights of compound 1 and compound 2.

References

ATSDR, 1995a, *Toxicological Profile for Naphthalene, 1-Methylnaphthalene, and 2-Methylnaphthalene (Update)*. U.S Department of Health & Human Services, Agency for Toxic Substances and Disease Registry, Atlanta, GA; August, 1995. 200 p.

ATSDR, 1995b, *Toxicological Profile for Polycyclic Aromatic Hydrocarbons (PAHs) (Update).* U.S Department of

Table B-1. – Chemical parameter values for PAH compounds used for volatilization factor

Compound	CAS #	K_{oc} [a] (L/kg)	H′ [b] (unitless)	D_a (cm^2/s)	D_w (cm^2/s)	D_A [c] (cm^2/s)	VF [d] (m^3/kg)
acenaphthene	83-32-9	2.46×10^{3}	6.36×10^{-3}	4.21×10^{-2}	7.69×10^{-6}	9.37×10^{-7}	1.29×10^{5}
acenaphthylene	208-96-8	3.68×10^{3}	4.67×10^{-3}	4.24×10^{-2}	7.74×10^{-6}	4.64×10^{-7}	1.84×10^{5}
anthracene	120-12-7	1.10×10^{4}	2.67×10^{-3}	3.24×10^{-2}	7.74×10^{-6}	6.88×10^{-8}	4.78×10^{5}
benz[*a*]anthracene	56-55-3	2.77×10^{5}	1.37×10^{-4}	5.10×10^{-2}	9.00×10^{-6}	2.53×10^{-10}	7.88×10^{6}
benzo[*a*]pyrene	50-32-8	2.31×10^{5}	4.63×10^{-5}	4.30×10^{-2}	9.00×10^{-6}	1.17×10^{-10}	1.16×10^{7}
benzo[*b*]fluoranthene	205-99-2	6.33×10^{5}	4.55×10^{-3}	2.26×10^{-2}	5.56×10^{-6}	1.41×10^{-9}	3.33×10^{6}
benzo[*ghi*]perylene	191-24-2	1.26×10^{6}	5.90×10^{-5}	4.11×10^{-2}	8.60×10^{-6}	9.04×10^{-12}	4.17×10^{7}
benzo[*k*]fluoranthene	207-08-9	6.33×10^{5}	3.40×10^{-5}	2.26×10^{-2}	5.56×10^{-6}	1.99×10^{-11}	2.81×10^{7}
chrysene	218-01-9	2.01×10^{5}	3.88×10^{-3}	2.48×10^{-2}	6.21×10^{-6}	4.15×10^{-9}	1.94×10^{6}
dibenz[*ah*]anthracene	53-70-3	1.33×10^{6}	6.03×10^{-7}	2.02×10^{-2}	5.18×10^{-6}	4.28×10^{-12}	6.05×10^{7}
fluoranthene	206-44-0	1.10×10^{4}	6.60×10^{-4}	3.02×10^{-2}	6.35×10^{-6}	1.62×10^{-8}	9.84×10^{5}
fluorene	86-73-7	5.03×10^{3}	2.61×10^{-3}	3.63×10^{-2}	7.88×10^{-6}	1.64×10^{-7}	3.09×10^{5}
indeno[123-*cd*]pyrene	193-39-5	1.77×10^{6}	6.56×10^{-5}	1.90×10^{-2}	5.66×10^{-6}	9.53×10^{-12}	4.06×10^{7}
1-methyl naphthalene	90-12-0	1.71×10^{3}	1.47×10^{-2}	5.60×10^{-2}	7.12×10^{-6}	4.12×10^{-6}	6.17×10^{4}
2-methyl naphthalene	91-57-6	1.87×10^{3}	2.08×10^{-2}	5.60×10^{-2}	7.12×10^{-6}	5.26×10^{-6}	5.46×10^{4}
naphthalene	91-20-3	8.28×10^{2}	1.98×10^{-2}	5.90×10^{-2}	7.50×10^{-6}	1.19×10^{-5}	3.63×10^{4}
phenanthrene	85-01-8	6.32×10^{3}	1.08×10^{-3}	3.24×10^{-2}	7.74×10^{-6}	4.76×10^{-8}	5.74×10^{5}
pyrene	129-00-00	6.21×10^{4}	4.51×10^{-4}	2.72×10^{-2}	7.24×10^{-6}	1.83×10^{-9}	2.93×10^{6}

[a] see Attachment C
[b] dimensionless Henry's law constant = H (atm-m^3/mol) × 41 (@ 20°C) (U.S. EPA, 1996)
[c] calculated from equation 11
[d] calculated from equation 10

Health & Human Services, Agency for Toxic Substances and Disease Registry, Atlanta, GA; August, 1995. 458 p.

Jury, W.A., W.F. Spencer, and W.J. Farmer, 1983, Behavior assessment model for trace organics in soil: I -- Model description. *Journal of Environmental Quality*, v. 12, no. 4, p. 558-564.

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U.S. EPA, 1991, *Risk Assessment Guidance for Superfund. Volume 1-- Human Health Evaluation Manual (Part B. Development of Risk-Based Preliminary Remediation Goals). Interim*. U.S. Environmental Protection Agency, Office of Emergency and Remedial Response, Washington, DC, Publication 9285.7-01B. EPA/540/R-92/003, 54 p. [NTIS # PB92-963333]

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Attachment C

Methodology Used for Development of RCLs Based on Protection of Groundwater Quality

The suggested generic residual contaminant levels (RCLs) for the PAHs based on protection of groundwater quality are calculated using a soil:water partitioning equation, which relates the adsorbed and dissolved concentrations of a compound, to represent the unsaturated zone, combined with a generic groundwater mixing zone to represent the additional reduction in concentration due to dilution and attenuation in groundwater. The soil concentrations are adjusted to reflect the concentration that would be measured in a soil sample, which is the sum of the contaminant mass in the adsorbed and dissolved phases divided by the dry bulk density of the soil.

The combination of the static groundwater mixing zone based on simple volumetric relationships with a relatively high recharge rate and simple soil:water partitioning appears to provide a reasonable balance of conservative and non-conservative assumptions. Therefore, it is considered appropriate for use in developing *generic* soil cleanup levels. However, it is *not* appropriate for use in site-specific determinations. In such cases the balance of assumptions incorporated into the generic mixing zone equation can, and likely will, be seriously violated.

Development of Soil:Water Partitioning Equation for the Unsaturated Zone

The methodology used to estimate contaminant release from soil in leachate is based on linear equilibrium soil:water partitioning. If adsorption is linear with respect to concentration, soil:water partitioning is described by the ratio of the equilibrium concentrations in the sorbed and dissolved phases:

$$K_d = \frac{C_s}{C_w} \qquad (1)$$

where K_d is the soil:water distribution coefficient (L/kg); C_s is the concentration sorbed on soil (mg/kg); and C_w is the concentration in soil moisture (mg/L). Rearranging in terms of calculating the sorbed concentration, the basic soil:water partitioning equation is:

$$C_s = K_d \times C_w \qquad (2)$$

For hydrophobic organic compounds such as the PAHs, soil organic matter is the dominant sorbant in soil if the organic carbon content is above a critical level. Thus K_d can be normalized to the organic carbon content of the soil and can be approximated by a partitioning coefficient that is relatively independent of soil type by:

$$K_d = K_{oc} \times f_{oc} \qquad (3)$$

where K_{oc} is the organic carbon:water partitioning coefficient (L/kg) and f_{oc} is the organic carbon fraction of the soil (g/g).

To specify an RCL that can be compared to measured soil concentrations, adjusting the sorbed concentration derived above (C_s) to the total concentration measured in a soil sample (C_m) is appropriate. Contaminants in a soil sample can be associated with the soil solids, the soil water, and the soil air. The measured contaminant concentration in a soil sample is described by:

$$C_m = \frac{C_s \rho_b + C_w \theta + C_a \theta_a}{\rho_b} \qquad (4)$$

where C_m is the measured concentration in soil (mg/kg); ρ_b is the dry bulk density of the soil (g/cm^3); θ is the volumetric soil moisture content (cm^3/cm^3); C_a is the concentration in the soil air (mg/cm^3); and θ_a is the air-filled porosity of the soil (cm^3/cm^3). This equation assumes that soil solids, water, and gas are conserved during sampling. Soil gas is typically not conserved during sampling and the PAHs are not volatile to any significant extent. Therefore, for practical purposes the mass in soil air ($C_a\theta_a$) can be disregarded and Equation (4) can be reduced to:

$$C_m = \frac{C_s \rho_b + C_w \theta}{\rho_b} \qquad (5)$$

Substituting Equation (2) into Equation (5) and simplifying yields:

$$C_m = C_w \left(K_d + \frac{\theta}{\rho_b} \right) \qquad (6)$$

Substituting Equation (3) into Equation (6) yields:

$$C_m = C_\theta \left(K_{oc} f_{oc} + \frac{\theta}{\rho_b} \right) \qquad (7)$$

For RCL calculation, C_θ is the target soil moisture concentration for the leachate.

Development of Groundwater Mixing Zone

The purpose of the groundwater mixing zone is to incorporate consideration of how groundwater concentrations are measured for compliance with groundwater standards. Basing the soil cleanup levels on groundwater concentrations that would actually be measured in the field is reasonable from a conceptual standpoint. In practice, groundwater samples are taken from monitoring wells and sample the entire saturated screened interval of the well. A typical water table monitoring well would have a 10-foot screen and, ideally, will be centered on the water table. This provides a saturated screened interval of about 5 feet (152.4 cm).

Contaminant concentrations in soil moisture at the water table do not necessarily reflect the concentrations that would be expected to be measured in groundwater. Contaminant concentrations are reduced through a variety of dilution and attenuation processes in mixing with groundwater. Therefore, the contaminant concentration in groundwater is generally lower than the original concentration in soil leachate. This reduction in contaminant concentration can be expressed succinctly by the groundwater dilution-attenuation factor (DAF) which is the ratio of the original concentration in soil moisture to the concentration in groundwater.

The dilution and attenuation of contaminants in groundwater are dependent upon many factors, including: hydraulic conductivity, hydraulic gradient, dispersivity and diffusion, sorption, and biodegradation. None of these factors are consistent from site to site, making generic assumptions regarding appropriate values tenuous at best. The incorporation of mixing in groundwater into the development of generic soil cleanup levels is hampered by the inherently site-specific nature of the parameters governing water balance fluxes and groundwater flow.

Simple "Volumetric" Mixing Approach

The approach taken for development of the generic RCLs uses a simple "volumetric" mass balance calculation with no consideration of groundwater flow. The volume of water recharging groundwater can be considered to displace an equivalent volume of water in the mixing zone and be uniformly mixed. A groundwater dilution-attenuation factor (DAF) can be determined using a simple mass balance approach that mixes the mass of a contaminant in groundwater recharge into the volume of a groundwater mixing zone and allowing equilibrium partitioning of the contaminant between the dissolved and adsorbed phases within the mixing compartment. This is a "static" model based on simple volume and mass relationships. Thus, it is not "real" in any physical sense. The simple groundwater mixing zone presented here was specifically developed for determination of **generic** RCLs. It is *not* appropriate and should *not* be used for any other purpose.

The mass of a compound in groundwater recharge can be defined as:

$$C_\theta \, x \, y \, R \, \theta \tag{8}$$

where C_θ is the concentration of the compound in the soil moisture (μg/L); x and y are the length and width of the compartment (cm), respectively; R is the average amount of groundwater recharge (cm); and θ is the volumetric soil moisture content (cm^3/cm^3). Assuming equilibrium partitioning, the total mass of a compound in the groundwater mixing zone is equal to the sum of the mass in the dissolved phase and the mass adsorbed to aquifer solids. Thus, the total mass of the compound in the groundwater mixing zone is:

$$C_w \, x \, y \, d \, n \; + \; C_s \, x \, y \, d \, \rho_b \tag{9}$$

where C_w and C_s are the concentrations of the compound dissolved in groundwater (µg/L) and adsorbed to aquifer solids (µg/kg), respectively; *d* is the depth (thickness) of the groundwater mixing zone below the water table (cm); *n* is the porosity of the aquifer material; and ρ_b is the dry bulk density of the aquifer material (g/cm^3). The equilibrium concentrations of a compound in the dissolved and adsorbed phases can be related by the linear soil:water partitioning equation:

$$C_s = K_d \times C_w \tag{10}$$

where K_d is the soil:water distribution coefficient (L/kg), which is commonly approximated from the organic carbon:water partitioning coefficient, which represents the soil:water distribution coefficient normalized to the organic carbon content of the aquifer solids, by:

$$K_d = K_{oc} \times f_{oc} \tag{11}$$

where K_{oc} is the organic carbon:water partitioning coefficient (L/kg) and f_{oc} is the organic carbon fraction of the aquifer solids (g/g). Substituting Equations (10) and (11), Equation (9) can be rewritten in terms of the concentration in the dissolved phase:

$$C_w\, x\, y\, d\, n + C_w\, K_{oc}\, f_{oc}\, x\, y\, d\, \rho_b \tag{12}$$

Combining like terms, Equation (12) can be simplified to:

$$C_w\, x\, y\, d \left(K_{oc}\, f_{oc}\, \rho_b + n\right) \tag{13}$$

Thus, a mass balance for transferring the mass of a compound in groundwater recharge from the unsaturated zone into the groundwater mixing zone can be described by:

$$C_\theta\, x\, y\, R\, \theta = C_w\, x\, y\, d \left(K_{oc}\, f_{oc}\, \rho_b + n\right) \tag{14}$$

Rearranging Equation (14) and canceling like terms give:

$$C_\theta = C_w \frac{d}{R\,\theta} \left(K_{oc}\, f_{oc}\, \rho_b + n\right) \tag{15}$$

where the dilution-attenuation factor (DAF) for the groundwater mixing zone is:

$$\mathrm{DAF} = \frac{d}{R\,\theta} \left(K_{oc}\, f_{oc}\, \rho_b + n\right) \tag{16}$$

By substituting the target groundwater concentration of the compound for C_w in equation (15), the term in (16) becomes the dilution attenuation factor relating the target concentration of a compound in soil moisture to the dissolved concentration in the groundwater mixing zone.

Algorithm for Generic RCL for Migration to Groundwater Pathway

$$\text{Residual Contaminant Level (mg/kg)} = \text{PAL} \times 10^{-3}\ \text{mg}/\mu\text{g} \times \left(K_{oc} f_{oc} + \frac{\theta}{\rho_b} \right) \times \text{DAF} \qquad (17)$$

where

$$\text{DAF} = \frac{d}{R\,\theta} \left(K_{oc} f_{oc} \rho_b + n \right) \qquad (18)$$

Parameter/Definition (units)	**Default**
PAL/preventive action limit (µg/L)	chemical-specific
K_{oc}/organic carbon:water partitioning coefficient (L/kg)	chemical-specific
f_{oc}/fractional organic carbon content (g/g)	0.001
θ/average volumetric soil moisture content of unsaturated zone (cm^3/cm^3)	0.2
n/porosity (cm^3/cm^3)	0.43
d/depth of groundwater mixing zone (cm)	152.4
R/annualized groundwater recharge (cm)	25.4
ρ_b/soil dry bulk density (g/cm^3)	1.5

Target Groundwater Concentrations

Target groundwater concentrations for the suggested generic RCLs for the PAHs are based on preventive action limits (PALs) for the compounds for which PALs are available. For the other PAH compounds, a target groundwater concentration equivalent to the PAL was determined as provided in s. NR 720.19(4)(a) and s. NR 722.07(2)(b)2, Wis. Adm. Code.

For noncarcinogenic compounds, s. 160.13, Wis. Stats., requires that an enforcement standard be developed assuming exposure for a 10-kg child ingesting one (1) liter of water per day. The resulting calculation for the enforcement standard is (Anderson et al, 1992):

$$\text{Enforcement Standard } (\mu\text{g/L}) = \frac{\text{RfD} \times 10\ \text{kg}}{1\ \text{L/d}} \times 1000\ \mu\text{g/mg} \qquad (19)$$

where RfD is the oral reference dose for the compound (mg/kg-d).

For carcinogenic compounds, s. 160.13, Wis. Stats., provides that enforcement standards are developed based on a lifetime excess cancer risk of 1×10^{-6}. The Department of Health and Social Services uses assumed exposure for a 70-kg adult ingesting two (2) liter of water per day for a 70-year lifetime. The resulting calculation for the enforcement standard is (Anderson et al, 1992):

$$\text{Enforcement Standard } (\mu g/L) = \frac{1\times10^{-6} \times 70 \text{ kg}}{SFo \times 2 \text{ L/d}} \times 1000 \ \mu g/mg \qquad (20)$$

where SFo is the oral cancer slope factor for the compound ($(mg/kg\text{-}d)^{-1}$).

The preventive action limit is determined as a percentage of the enforcement standard. The specific percentages provided by s. 160.15, Wis. Stats., for substances of human health concern are 10% for carcinogens and 20% for noncarcinogens. The enforcement standards are developed assuming 100% of the exposure to the chemical is from drinking water. Thus, the percentage reductions used for determining the preventive action limits are essentially equivalent to using a target excess cancer risk of 1×10^{-7} for carcinogens and a target hazard quotient of 0.2 for noncarcinogens. For class D carcinogens that are evaluated using a cancer endpoint, the PAL is equivalent to assuming a 2×10^{-7} target excess cancer risk.

K_{oc} Values for PAHs

Soil:water partitioning coefficients (K_d) were estimated using the organic carbon:water partitioning coefficient (K_{oc}). K_{oc} values for the PAHs were determined from an evaluation of available measured values or estimated if no measured values were available. A Microsoft Excel 5.0 spreadsheet containing the compiled data and analysis is available in electronic format and can be downloaded via modem from the Bureau for Remediation and Redevelopment BBS at (608) 261-6455 (8-N-1).

Values for K_{oc} reported in the literature for the PAHs exibit a wide range of variation. Reported measured values for a given compound sometimes vary over several orders of magnitude. An extensive literature search was conducted to identify available measured values for K_{oc} and original references were consulted wherever possible. A summary of results are shown in Table C-1. The K_{oc} values used for the suggesed generic RCLs are based on the lower 95% confidence limit for the mean of measured log K_{oc} values for each compound.

Measured K_{oc} values were not found in the literature for several of the PAH compounds. For these compounds, a regression equation was developed based on the available measured PAH log K_{oc} values and the octanol:water partitioning coefficient (K_{ow}). Linear regression of measured values for log K_{oc} on log K_{ow} yielded the following relationship:

$$\log K_{oc} = 1.02 \log K_{ow} + 0.467 \qquad (21)$$

where K_{ow} is the octanol:water partitioning coefficient.

A summary of the estimated K_{oc} values is shown in Table C-2. The estimated K_{oc} values used for the suggested generic RCLs are based on the lower 95% confidence limit for the estimated mean from the regression equation.

Table C-2. – Summary of estimated K_{oc} values for PAH compounds without measured K_{oc} values based on octanol:water partition coefficient (K_{ow})

Compound	CAS #	log K_{ow} [a]	Est. log K_{oc} [a]	Est. log K_{oc} [c] lower 95% C.L.	Est. K_{oc} [d] lower 95% C.L.
benzo[*b*]fluoranthene	205-99-2	6.20	5.86 ± 0.06	5.80	6.33×10^5
benzo[*ghi*]perylene	191-24-2	6.50 [e]	6.17 ± 0.07	6.10	1.26×10^6
benzo[*k*]fluoranthene	207-08-9	6.20	5.86 ± 0.06	5.80	6.33×10^5
chrysene	218-01-9	5.70	5.35 ± 0.05	5.30	2.01×10^5
indeno[123-*cd*]pyrene	193-39-5	6.65	6.32 ± 0.07	6.25	1.77×10^6

[a] log octanol:water partitioning coefficient; values from U.S. EPA (1996) unless otherwise indicated
[b] estimated mean log organic carbon:water partitioning coefficient; ± indicates 95% confidence interval
[c] estimated log K_{oc} value at the lower 95% confidence limit for the mean log K_{oc} values
[d] estimated K_{oc} value at the lower 95% confidence limit for the mean log K_{oc} value
[e] value from ATSDR (1995)

References

Table C-1. – Summary of data on measured K_{oc} values for PAH compounds

Compound	CAS #	Mean log K_{oc} [a]	95% C.I. [b]	log K_{oc} [c] lower 95% C.L.	K_{oc} [d] lower 95% C.L.	# meas. [e]
acenaphthene	83-32-9	3.60	± 0.21	3.39	2.46×10^3	3
acenaphthylene	208-96-8	3.72	± 0.15	3.57	3.68×10^3	3
anthracene	120-12-7	4.23	± 0.19	4.04	1.10×10^4	18
benz[*a*]anthracene	56-55-3	5.74	± 0.30	5.44	2.77×10^5	7
benzo[*a*]pyrene	50-32-8	5.85	± 0.49	5.36	2.31×10^5	12
benzo[*b*]fluoranthene	205-99-2			none found		
benzo[*ghi*]perylene	191-24-2			none found		
benzo[*k*]fluoranthene	207-08-9			none found		
chrysene	218-01-9			none found		
dibenz[*ah*]anthracene	53-70-3	6.25	± 0.13	6.12	1.33×10^6	14
fluoranthene	206-44-0	4.38	± 0.34	4.04	1.10×10^4	9
fluorene	86-73-7	3.88	± 0.18	3.70	5.03×10^3	7
indeno[123-*cd*]pyrene	193-39-5			none found		
1-methyl naphthalene	90-12-0	3.37	± 0.14	3.23	1.71×10^3	14
2-methyl naphthalene	91-57-6	3.46	± 0.19	3.27	1.87×10^3	8
naphthalene	91-20-3	3.01	± 0.09	2.92	8.28×10^2	59
phenanthrene	85-01-8	4.01	± 0.21	3.80	6.32×10^3	18
pyrene	129-00-00	4.84	± 0.05	4.79	6.21×10^4	46

[a] arithmetic mean of measured log K_{oc} values
[b] 95% confidence interval for the mean of log K_{oc} values
[c] log K_{oc} value at the lower 95% confidence limit for the mean log K_{oc} values
[d] K_{oc} value at the lower 95% confidence limit for the mean log K_{oc} value
[e] number of measured values

ATSDR, 1995, *Toxicological Profile for Polycyclic Aromatic Hydrocarbons (PAHs) (Update).* U.S Department of Health & Human Services, Agency for Toxic Substances and Disease Registry, Atlanta, GA; August, 1995. 458 p.

U.S. EPA, 1996, *Soil Screening Guidance*: *Technical Background Document*. U.S. Environmental Protection Agency, Office of Emergency and Remedial Response, Washington, DC. EPA/540/R-96/128.

Attachment D

Example Determination of Soil Cleanup Levels for PAHs Using the Benzo[a]pyrene-Equivalent Concentration Approach

The application of the benzo[*a*]pyrene-equivalent concentration approach involves conversion of the measured concentrations of PAH compounds to an equivalent concentration (with regard to toxic potency) of benzo[*a*]pyrene. This concentration can be compared to an RCL developed for the PAH mixture in terms of a benzo[a]pyrene-equivalent concentration.

Calculation of Benzo[a]pyrene-Equivalent Concentrations

The equivalent concentration of benzo[*a*]pyrene is determined by multiplying the measured concentration of a PAH compound by its relative potency factor:

$$C_{B[a]P\text{-equiv}} = C_n \times RPF_n \qquad (1)$$

where C_n is the measured concentration of the PAH compound in soil (mg/kg) and RPF_n is the relative potency factor for that compound. The sum of the B[*a*]P-equivalent concentrations for the individual compounds yields the B[*a*]P-equivalent concentration for the PAH mixture:

$$C_{B[a]P\text{-equiv}} = \sum \left(C_n \times RPF_n\right) \qquad (2)$$

Table D-1 shows the benzo[*a*]pyrene-equivalent concentrations determined for some example PAH data; please note that calculated BaP-equivalent concentrations typically will be much less than the measured PAH concentrations.

Table D-1. – An example comparison of measured and benzo[*a*]pyrene-equivalent concentrations for a contaminated soil (mg/kg)

				BaP_{equiv} Conc.	
Detected compound	CAS #	RPF	Measured Conc.	Carcinogenic PAHs	All detected PAHs
acenaphthene	83-32-9	0.001	0.22		0.00022
acenaphthylene	208-96-8	0.001	0.12		0.00012
anthracene	120-12-7	0.01	1.3		0.013
benz[*a*]anthracene	56-55-3	0.1	5.5	0.55	0.55
benzo[*a*]pyrene	50-32-8	1	4.2	4.2	4.2
benzo[*b*]fluoranthene	205-99-2	0.1	3.9	0.39	0.39
benzo[*ghi*]perylene	191-24-2	0.01	3.3		0.033
benzo[*k*]fluoranthene	207-08-9	0.01	3.3	0.033	0.033
chrysene	218-01-9	0.001	4.9	0.0049	0.0049
dibenz[*ah*]anthracene	53-70-3	1	1.6	1.6	1.6
fluoranthene	206-44-0	0.001	6.2		0.0062
fluorene	86-73-7	0.001	1.4		0.0014
indeno[123-*cd*]pyrene	193-39-5	0.1	3.9	0.39	0.39
1-methyl naphthalene	90-12-0	0.001	1.1		0.0011
2-methyl naphthalene	91-57-6	0.001	2.1		0.0021
naphthalene	91-20-3	0.001	0.65		0.00065
phenanthrene	85-01-8	0.001	2.1		0.0021
pyrene	129-00-00	0.001	8.8		0.0088
Subtotal PAHs			54.59		
Total BaP-equivalent				7.1679	7.23659

Calculating RCLs for Benzo[a]pyrene-Equivalent Concentrations

Soil cleanup levels based on benzo[*a*]pyrene-equivalent concentrations are then developed using the risk-based algorithms for carcinogenic compounds in Attachment B and the cancer slope factor for benzo[*a*]pyrene (7.3 $(mg/kg\text{-}d)^{-1}$). The RCLs can be developed based on either the "carcinogenic" PAHs or based on all the PAHs in the mixture. A combined target cancer risk level can be determined for the carcinogenic PAHs alone or for all the detected PAHs, up to the cumulative excess cancer risk limit of 1×10^{-5} specified in s. NR 720.11(3), Wis. Adm. Code.

The combined target excess cancer risk level is determined by multiplying the target risk for individual compounds by the number of compounds in the assessment. The generic RCLs in Table 2 of ch. NR 720, Wis. Adm. Code, are based on a target excess cancer risk for individual compounds of 1×10^{-7} for the non-industrial (residential) scenario and 1×10^{-6} for the industrial scenario. The target risk for individual compounds for the non-industrial scenario can be modified for *in situ* contaminated soil to 1×10^{-6} on a site-specific basis under s. NR 720.19(5)(a), Wis. Adm. Code.

For the example PAH data in Table D-1, since there are seven (7) carcinogenic PAHs present, this assessment would use a combined target excess cancer risk level of 7×10^{-7} for the non-industrial (residential) scenario and 7×10^{-6} for the industrial scenario. The resultant soil cleanup level equivalent to the generic RCLs (expressed as benzo[*a*]pyrene-equivalent concentration) for direct ingestion calculated using Equation 4 from Attachment B for the industrial exposure scenario and the combined target risk of 7×10^{-6} is:

$$\text{RCL} = \frac{(7\times10^{-6}) \times 70 \times 70 \times 365}{7.3 \times 10^{-6} \times 250 \times 25 \times 100} = 2.7 \text{ mg/kg}$$

The resultant soil cleanup level equivalent to the generic RCLs (expressed as benzo[*a*]pyrene-equivalent concentration) for direct ingestion calculated using Equation 3 from Attachment B for the non-industrial (residential) scenario and the combined target risk of 7×10^{-7} is:

$$\text{RCL} = \frac{(7\times10^{-7}) \times 70 \times 365}{7.3 \times 10^{-6} \times 350 \times 114} = 0.061 \text{ mg/kg}$$

This value for the non-industrial scenario can be modified for *in situ* contaminated soil using a combined target risk of 7×10^{-6} to 0.61 mg/kg on a site-specific basis.

Similarly, benzo[*a*]pyrene-equivalent RCLs can be developed for all the PAHs present in the mixture. For the example PAH data in Table D-1, since there are eighteen (18) PAHs present, this assessment would use a combined target excess cancer risk level of 1.8×10^{-6} (= $18 \times 1\times10^{-7}$) for the non-industrial (residential) scenario. However, for the industrial scenario a combined target excess cancer risk level of 1×10^{-5} would be used since $18 \times 1\times10^{-6} = 1.8\times10^{-5}$ which exceed the cumulative risk limit specified in s. NR 720.19(5)(a), Wis. Adm. Code. The resultant soil cleanup level equivalent to the generic RCLs (expressed as benzo[*a*]pyrene-equivalent concentration) for direct ingestion calculated using Equation 4 from Attachment B for the industrial exposure scenario and the combined target risk of 1×10^{-5} is:

$$\text{RCL} = \frac{(1\times10^{-5}) \times 70 \times 70 \times 365}{7.3 \times 10^{-6} \times 250 \times 25 \times 100} = 3.9 \text{ mg/kg}$$

The resultant soil cleanup level equivalent to the generic RCLs (expressed as benzo[*a*]pyrene-equivalent concentration) for direct ingestion calculated using Equation 3 from Attachment B for the non-industrial (residential) scenario and the combined target risk of 1.8×10^{-6} is:

$$\text{RCL} = \frac{(7\times10^{-7}) \times 70 \times 365}{7.3 \times 10^{-6} \times 350 \times 114} = 0.061 \text{ mg/kg}$$

Again, the value for the non-industrial scenario can be modified for *in situ* contaminated soil. However, in this case a combined target excess cancer risk level of 1×10^{-5} would be used since $18 \times 1\times10^{-6} = 1.8\times10^{-5}$ which exceeds the cumulative risk limit specified in s. NR 720.19(5)(a), Wis. Adm. Code. The resultant soil cleanup level equivalent to the generic RCLs (expressed as benzo[*a*]pyrene-equivalent concentration) for direct ingestion calculated using Equation 3 from Attachment B for the non-industrial (residential) scenario and the combined target risk of 1×10^{-5} is:

$$\text{RCL} = \frac{(1\times10^{-5}) \times 70 \times 365}{7.3 \times 10^{-6} \times 350 \times 114} = 0.9 \text{ mg/kg}$$